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6. AUTHOR(S)
T. Alan Hatton

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
David H. Koch School of Chemical Engineering Practice
Massachusetts Institute of Technology
25 Ames Street, Cambridge, MA 02139-4307

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13. ABSTRACT (Maximum 200 words)

Ten advanced chemical engineering research projects were executed at the US Army Natick RD&E Center over a three month period by students of the David H. Koch School of Chemical Engineering Practice, administered by the Massachusetts Institute of Technology. The projects resulted in significant technical conclusions and recommendations which are to be implemented by the Center. Project areas included (i) Optimization of the energy output from the flameless ration heater, (ii) Comparison of equipment for drying food, (iii) Characterization of the vapor compression microclimate cooling system, (iv) Recycling of melt-spun fiber, (v) Energy efficiency of a modular appliance technology, centralized heating (MATCH) kitchen, (vi) Identification of the essential characteristics of an extruded meat/carbohydrate product, (vii) Evaluation of selectively permeable fabrics for chemical protection, (viii) Permeation and sorption characteristics of elastomeric chemical barriers, (ix) Interaction of moving droplets with fabric surfaces, and (x) Systems analysis for the chemically and biologically protected shelter.

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ADVANCED CHEMICAL ENGINEERING RESEARCH

FINAL REPORT

T. ALAN HATTON
CHEVRON PROFESSOR OF CHEMICAL ENGINEERING
AND DIRECTOR, DAVID H. KOCH SCHOOL OF CHEMICAL ENGINEERING PRACTICE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE MA 02139

OCTOBER 28, 1994

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1 Introduction

A station of the David H. Koch School of Chemical Engineering Practice of the Massachusetts Institute of Technology was established at the US Army Research, Development and Engineering Center, Natick MA, to conduct advanced chemical engineering research in areas of direct interest to the Natick Laboratories. A total of ten one-month projects was completed during the three-month grant period, each project being undertaken by a two- or three-member team. In all, sixteen graduate students participated in this program, eight for the first four-week project period, and a second group of eight for the two subsequent project periods. The work was supervised by members of the MIT teaching staff, who were on site for the entire contract period, with overall coordination from MIT by the PI.

The US Army Natick Research Development and Engineering Center is the only Government laboratory or center that has the capability and physical resources to perform a range of studies related to the chemical engineering of chemical protective material properties, individual cooling system design/operation, and food processing techniques, that are of importance to the Department of the Army. However, they do not have the necessary in-house personnel to conduct needed experiments, modelling studies and optimization of (i) heat stress reduction, increased chemical resistance, and physical properties of chemical protective materials, (ii) efficiency, power utilization, cooling effect, and related trade-off analyses of individual cooling systems, and (iii) production engineering for food processing. Because of the unique structure of the David H. Koch School of Chemical Engineering Practice, with its proven record in providing rapid results in industrial production, research and development operations, the graduate students of this program were able to provide the expertise and chemical engineering skills required for efficient execution of these projects. The structured, intense nature of the program resulted in a higher research productivity than can be expected in more usual research and development settings, both in academic circles, and in industrial and Government R&D laboratories.

2 Background on the David H. Koch School of Chemical Engineering Practice

The School of Chemical Engineering Practice was established in 1916 to provide a practical complement to the academic studies of chemical engineering students at MIT. While it has maintained its original focus, it has adapted with the times to become a highly sought-after program awarding the degree of Master of Science in Chemical Engineering Practice (MSCEP). The graduates from this program are regarded as being well-trained in communications, team work, group and time management, and in responding to technical issues. The program consists of two semesters of graduate course work on the fundamentals and applied aspects of transport phenomena, thermodynamics, systems engineering, and reactor design and kinetics. The students are also required to take courses on advance mathematics and applied chemistry. A third semester is spent doing project work at each of two industrial sites, or 'Stations'. Typically eight or nine students are in residence at a station for one or two months, where they work on projects in teams of two or three, each project being of a month duration. Approximately half the students participating in the program are doctoral candidates, while the rest are students who have come to MIT specifically to participate in the MSCEP program. At the stations, the students are supervised by resident MIT teaching staff, a Director and an Assistant Director, hired specifically for this task. The Cambridge Director (the Principal Investigator on this project) is responsible for the overall operation of the program. Following completion of their projects at one station, the group move on to the next station. Currently, we run two stations year round, at Dow Chemical Company in Midland, MI, and Merck and Company at their West Point, PA, facilities. As needed, we operate a third station over the summer period at an additional facility, in this case, the US Army Natick RD&E Laboratories.

3 Summary of Research Projects

The projects undertaken by the student groups are summarized in this section. A final report for each of these projects is available from the PI, and has been furnished to the US Army RD&E Center at Natick, MA. These will be issued as formal reports by the Natick Center.

3.1 Optimization of the energy output from the flameless ration heater (Students: Tani Chen, Suman Banerjee)

The factors affecting the efficiency of heat output of the Flameless Ration Heater (FRH), which produces heat from the reaction of magnesium with water, were studied with the goal of providing guidelines for improved efficiency. Parameters such as the FRH pore size, pore density, magnesium particle distribution, pad density, and the effective porosity were examined closely using image analysis techniques. It was observed that the top surface of the pad has more magnesium particles and pores than the bottom surface, which can have significant consequences for the distribution of water and heating rates throughout the pad. The effect of the magnesium hydroxide by-product and the role of the polyethylene matrix that holds the FRH together were examined by reacting the pads under various conditions and measuring the volume of hydrogen gas produced. The magnesium hydroxide coating inhibits the reaction and there is no significant encapsulation of the magneium particles by the polyethylene matrix. Alternate cover designs, including various materials and distributions of holes in the cover, were also studied, an observation being that more holes give a better reaction profile. Finally, an alternative manufacturer's FRH was investigated to determine its relative strengths and merits. Based on these studies, recommendations for improving the design of the FRH include increasing its porosity, distributing the magnesium partricles more evenly, adding slightly more water, and increasing the number of holes in the fiberboard cover.

3.2 Comparison of equipment for drying foods (Students: Markus Langner, Fred Calhoun, Arpan Mahorowala)

This study presents a comparison of equipment for drying peas. Dryers investigated were the ball dryer (BD), the centrifugal fluid bed dryer (CF), and the microwave augmented freeze dryer (MW). Peas were dried in each unit from 78% to 5–10% moisture. The dried peas were rehydrated and subjected to quality tests for color and texture. Similar measurements, which served as controls, were made on frozen peas that were boiled.

The MW gave the best quality peas. There was no significant difference in the quality between the MW and control peas. The color of the BD and CF peas was different than that of the controls. The CF peas were the hardest.

An economic comparison between the technologies was also made. Fixed capital costs for drying capacities of 1000 and 10000 lb. water removed per hour were calculated from purchased equipment costs listed by Sapakie and Renshaw (22). Relative utility costs were estimated from the measurements made on the pilot scale equipment. Operating costs were obtained by scaling the utility costs from Sapakie and Renshaw and including labor costs. Finally, manufacturing costs were calculateld based on the assumptions of Sapakie and Renshaw. The manufacturing costs of the CF were marginally less than those of the BD. The MW manufacturing costs were about 4 times as high as those of the BD. For a 1000 lb/hr capacity BD, CF, and MW, the manufacturing costs were 32, 25 and 116 cents/lb dried peas respectively. This compares with 129 cents/lb dried peas for the current freeze drying process.

The trade–off between quality and economics is discussed. Several drying strategies aimed at achieving better product quality at a lower cost are recommended. For the pilot scale equipment, operating conditions and equipment modifications are recommended.

3.3 Characterization of the vapor compression microclimate cooling system (Students: Daniel Winkelmann, Stephen Conway, Nabil Triki)

A model characterizing the Microclimate Cooling (MCC) system is developed based on thermodynamic principles and incorporates experimental values for the efficiency of the compressor, the heat transfer coefficients and the temperature driving force for the condenser and the evaporator. These equations were implemented using Xess, a spreadsheet package. Simulations varying different parameters were run to calculate the size and weight of the unit. The model can be used for different operating conditions and to generate graphs showing at a glance which combination of parameters fulfills the specifications.

For a MCC providing 300 Watts of cooling for 4 hours at an ambient temperature of 85_F at a compression ratio of 4.0, these operating parameters result in the lowest weight of 19.5 pounds:

- Compressor speed: 3300 RPM
- Water flowrate: 10 GPH
- Heat transfer area of the condenser: 130 in^2
- Heat transfer area of the evaporator: 57 in^2
- Suction pressure of 45 psia

Batteries make about half the weight of the unit and significant weight reduction can be achieved by:

- Increasing compressor efficiency to reduce power required
- Designing new types of compressors which would operate adequately at high speeds.
- Increasing battery power density compared to the lithium/Sulfur Dioxide units now in use.

3.4 Recycling of melt-spun fiber (Students: Hongming Chen, Charlene Suwanabhand, Lei Zhang)

A recycling process was studied to handle waste material generated by the U.S. Army Natick Fiber Plant. Accumulated waste fibers were granulated, extruded, pelletized, mixed with new material and respun into fibers. Fibers that meet classified government standards for denier, tenacity, color matching and color fastness were produced from a mixture containing 10% recycled material at current operating conditions. Higher recycle ratios were processed at lower temperatures due to the decrease in viscosity and molecular weight caused by repeated extrusion. Recycled material was shown to have the same glass transition and melting point temperatures as new material; experiments to quantify viscosity and molecular weight changes are recommended. Further experiments are necessary to correct the color of fibers containing more than 10% recycled material. If acceptable fibers are produced with at least 10% recycled material, an immediate payback of $42,400 from accumulated waste with an additional savings of $8,500/yr in material costs is expected, not including the avoided cost of disposal. Acceptable fibers could not be produced at recycle ratios greater than 30% because the polymer mixture separated in the spinning

extruder due to differences in viscosity. Irregularly–shaped recycled pellets also bridged in the spinning extruder feed neck; the crammer feeder for the pelletizing extruder was redesigned to better handle granulated waste fibers and produce more uniform recycled pellets. Further experiments are necessary to evaluate the improved equipment.

3.5 Energy efficiency of a modular appliance technology, centralized heating (MATCH) kitchen (Students: Vivian Cheung, Bernard Wong)

The energy efficiency of a MATCH field kitchen prototype was characterized. The prototype is equipped with four cooking appliance modules: a griddle, a deep fat fryer, a kettle, and an oven. The average idle energy consumption of the system, with all modules turned off, was found to be 43,000 Btu/hr. The performance of the system with only one module active at a time was investigated using water boil tests, water heating tests, and food cooking tests. Based on total fuel input, the module efficiency in water boiling was found to be 52% for the griddle, 63% for the fryer and 72% for the kettle. The module efficiency in water heating was measured as 37% for the griddle, 37% for the fryer, 35% for the kettle and 8% for the oven. The griddle has an energy efficiency of 28% in cooking hamburger patties and the fryer 17% in making French fries. The overall efficiency of the system was observed to increase with the number of modules in use. With all four modules active simultaneously, the system was found to have an overall energy efficiency of 97%. A mathematical model was developed for predicting the overall energy efficiency under different system configurations and operating conditions.

3.6 Identification of the essential characteristics of an extruded meat/carbohydrate product (Students: Aleks Engel, Joydeep Goswami, Scott Johnston)

The sensory and physical properties of a new extruded meat–carbohydrate snack were studied. Extrusion parameters studied included food water content, screw speed, meat type, meat content, starch content and the total throughput through the reactor. The sensory properties studied were chewiness, tearability, perceived toughness, perceived density and overall appearance. An informal sensory panel rated sensory properties of the samples as compared to a given control sample while an informal consumer panel rated sensory properties on an absolute scale. Detailed statistical analyses were carried out to determine statistically significant sensory differences between samples. Physical properties tested included mechanical properties in tension, compression and shear as well as density and porosity. Water activity and pH were tested to determine resistance to spoilage. Sensory properties were correlated to the physical property tests. Tearability was found to be a function of mechanical toughness and shear force and shear work. Chewiness and perceived toughness were found to be a function of recoverable compression work. Sensory and physical properties were quantitatively correlated to extrusion parameters using multiple regression techniques. Most sensory and physical properties correlated well with feed water content and meat content. Young's modulus and maximum tensile stress did not correlate well with extrusion conditions.

3.7 Evaluation of selectively permeable fabrics for chemical protection (Students: Aleks Engel, Lei Zhang)

The transport properties of ChemPak LT, a new selectively permeable material, were investigated using a diffusion cell. From this preliminary analysis, ChemPak LT which is intended for chemical protective clothing was found to be very promising. The material was found to allow a flux of 2000 grams of water per day per m^2 to permeate through it at 32_C. The water to methanol diffusion selectivity was found to be better than 150:1. Since the chemical properties of methanol

are similar to water, the selectivity should be even better for larger and less polar compounds such as chemical warfare agents.

3.8 Permeation and sorption characteristics of elastomeric chemical barriers (Students: Bernard Wong, Scott Johnston)

The resistance to chemical warfare agent simulants (1,5 dichloropentane and triethyl phosphate) of seven types of chemical barrier materials were evaluated using the sorption and the permeation tests. The solubilities, diffusivities and chemical agent simulant breakthrough times in the barrier materials were measured. The diffusivities of dichloropentane in the materials were found to be of the order of 10^{-8} cm^2/s, with the Siebe North butyl rubber sample having the lowest value of 2.78×10^{-8} cm^2/s. Polyurethane samples dissolved in triethyl phosphate. All other materials studied except Trefsin thermoplastic elastomer absorbed negligible amounts of TEP. As a result, the diffusivity of TEP in these materials could not be calculated. The breakthrough time of dichloropentane through the barrier materials ranged from less than 0.5 hour to 22 hours, with the DSM thermoplastic elastomer sample having the longest breakthrough time. The Siebe North and Brunswick butyl rubbers and DSM and Novacor thermoplastics were concluded to be effective chemical barrier materials.

Mathematical models were developed to describe the sorption and permeation tests. Experimental results indicated that breakthrough time can be predicted as approximately one quarter of the square of sample thickness divided by the diffusivity.

3.9 Interaction of moving droplets with fabric surfaces (Students: Hongming Chen, Vivian Cheung)

The behavior of droplets falling onto fabrics was studied on both untreated (wicking) and Quarpel–treated (non–wicking) surfaces of Nyco7. Effects of droplet viscosity, surface tension, impact velocity, and impact fabric angle were evaluated. All four parameters were found to affect the liquid behavior on the non–wicking surface; no difference was observed in the case of the wicking surface. Liquid surface tension governs the spreading and splashing of liquid droplets on the non–wicking fabric. Viscosity affects the fluid roll–off as well as splashing when the liquid surface tension is high. Impact velocity determines the droplet kinetic energy and thus determines liquid splashing and rolling off. Impact fabric angle is critical for the liquid mobility on the fabric. It also affects liquid splashing during droplet impact. The dynamic interaction of droplets with fabric surfaces was found to be very different from the static case, especially for low surface tension liquids. The critical surface tension at which droplets start to spread on the non–wicking surface was determined to be between 32 dynes/cm and 38 dynes/cm.

3.10 Systems analysis for the chemically and biologically protected shelter (Students: Joydeep Goswami, Charlene Suwanabhand)

A systems analysis was performed on the Chemically and Biologically Protected Shelter (CBPS) to replace the current refrigerant (R–22) in the air conditioning system, to explore alternative power generation and power transmission systems and to reduce the total weight of the shelter. The maximum power requirements for the shelter were calculated to be 5.9 kW for Hot/Dry conditions (120_F, 3% relative humidity) and 25.6 kW for Basic Cold conditions (–25_F, 100% relative humidity). Additional insulation of the shelter reduced the power requirements to 4.9 kW for Hot/Dry conditions and 15.1 kW for Basic Cold conditions. The size of the existing evaporator and condenser coils are sufficient for R–22, R–134a and Suva AC–9000 for the maximum cooling loads expected. The existing compressor design is adequate for R–22 at an evaporating

temperature of 40_F and a condensing temperature of 140_F with 10_F of subcooling, but is inadequate for R–22 at higher condensing temperatures and for R–134a and Suva AC–9000 at all operating conditions. Suva AC–9000 requires fewer modifications to the compressor than R–134a and should be used as the replacement for R–22. Removing the 750 lb. hydraulic system allows 100 lb. of insulation to be added, reducing the maximum power requirement. A 15 kW Auxiliary Power Unit was found to be a feasible alternative to the current power generation system.

4 Participating Scientific Personnel

The scientific personnel particpating in this project are listed below.

MIT Staff:

Prof. T. Alan Hatton, Director of the School of Chemical Engineering Practice (PI)
Dr. C. Michael Mohr, Station Director (June)
Mr. Eric W. Anderson, Station Director (July and August)
Ms. Colleen Vandewoorde, Assistant Director (June)

MIT Students:

June:
Mr. Suman Banerjee
Mr. Tani Chen
Mr. Fred Colhoun
Mr. Stephen Conway
Mr. Makus Langner
Mr. Arpan Mahorowala
Mr. Nabil Triki
Mr. Daniel Winkelmann

July/August:
Ms. Hongming Chen
Ms. Vivian Cheung
Mr. Aleks Engel
Mr. Joydeep Goswami
Mr. Scott Johnston
Ms. Charlene Suwanabhand
Mr. Bernard Wong
Ms. Lei Zhang

All sixteen students will be awarded the degree of Master of Science in Chemical Engineering Practice. The requirements for this degree were satisfied in part by the work carried out at the US Army Natick RD&E facilities.

5 Conclusion

Ten different projects were executed by MIT Practice School student teams over a three month period at the US Army Natick RD&E Center. The projects resulted in significant technical conclusions and recommendations, most of which are to be implemented by the Center.